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Development of a superradiant collective optical laser

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14. ABSTRACT
We explored the potential of direct spectroscopy of ultra-narrow optical transitions of atoms localized in an optical cavity. In contrast to stabilization against a reference cavity which is the approach currently used for the most highly stabilized lasers, stabilization against an atomic transition does not suffer from the

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ultrastable lasers sensors metrology clocks

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Report Title

Development of a superradiant collective optical laser

ABSTRACT

We explored the potential of direct spectroscopy of ultra-narrow optical transitions of atoms localized in an optical cavity. In contrast to stabilization against a reference cavity which is the approach currently used for the most highly stabilized lasers, stabilization against an atomic transition does not suffer from the thermal noise problem. Spectroscopy of ultra-narrow optical transitions in a cavity operates in a very highly saturated regime in which non-linear effects such as bistability play an important role. We determined the fundamental limits for laser stabilization using direct spectroscopy of ultra-narrow atomic lines. We found that with current experimental technology laser linewidths of about 1 millihertz can be achieved whereas linewidths below 1 microhertz are possible in principle.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
2012/06/08 1! 2	M. Martin, D. Meiser, J. Thomsen, Jun Ye, M. Holland. Extreme nonlinear response of ultranarrow optical transitions in cavity QED for laser stabilization, Physical Review A, (12 2011): 0. doi: 10.1103/PhysRevA.84.063813

TOTAL: 1

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Contributed talk: David Tieri, Dominic Meiser and Murray Holland, "Cavity QED systems with group II atoms and the crossover between lasing and superradiance", DAMOP annual meeting of the American Physical Society, Atlanta, Georgia June 13-17 (2011).

Contributed talk: Dominic Meiser, Michael Martin, Jun Ye and Murray Holland, "Cavity enhanced nonlinear spectroscopy of ultra-narrow optical transitions", DAMOP annual meeting of the American Physical Society, Atlanta, Georgia, June 13-17 (2011).

Contributed poster: Murray Holland, Dominic Meiser and David Tieri, "Cavity QED with group II atoms", DAMOP annual meeting of the American Physical Society, Atlanta, Georgia, June 13-17 (2011).

Invited talk: Murray Holland, "Prospects for a superradiant laser", The 41st Winter Colloquium on the Physics of Quantum Electronics, Snowbird, Utah, Jan 2-6 (2011).

Number of Presentations: 4.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
2012/06/08 1!	1	Jun Ye, D. Meiser, M. J. Holland. Prospects for milli-hertz linewidth lasers using collective emission, 2010 IEEE International Frequency Control Symposium (FCS). 2010/06/01 00:00:00, Newport Beach, CA, USA. : ,

TOTAL: 1

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

College Scholar, University of Colorado Boulder, 2011

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Dominic Meiser	0.60
FTE Equivalent:	**0.60**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Murray Holland	0.10	
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Kayla Crosbie	0.50	Physics, B.Sc. Honors, Summa Cum Laude
FTE Equivalent:	**0.50**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 1.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 1.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 1.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment

Technology Transfer

Final Technical Report

Development of a superradiant collective optical laser

Murray John Holland

JILA and Department of Physics, University of Colorado, Boulder

Award No.: W911NF-10-1-0222 **End Date: 3/19/2011**

Foreword

Our research from the nine month STIR led to two publications representing the two main research efforts that were completed. These two research topics, the active and passive approaches, are linked by the common aim to employ the narrow linewidths of clock transitions in alkali-metal atoms to generate extremely coherent light. Demonstration of such light sources has the potential to revolutionize precision metrology, enabling the next generation of atomic clocks, with implications for a variety of applications in sensors and navigation.

Statement of the problem studied

Passive system

In a collaboration with the experimental group of Jun Ye at JILA, we investigated theoretically the extreme nonlinear response of ultranarrow optical transitions in cavity QED for the purpose of laser stabilization. This work was published in Physical Review A. The idea was to stabilize a laser against a reference gas, in the spirit of saturation spectroscopy, but employing atoms that have dipole moments that are five orders of magnitude smaller than those typically used. The consequence of using such atoms—*e.g.* light resonant with the clock transition of an ensemble of strontium-87 atoms—is that the saturation photon number becomes extremely small. In turn this means that weak optical fields of order a few photons can completely saturate the medium, and lead to extreme nonlinear optics in an unprecedented parameter regime.

We fully studied the signal to noise properties of such a system and considered the fundamental limits to the stability of the locked laser with current experimental technology.

Active system

The second system considered was the active device where energy is pumped incoherently to drive an ultranarrow transition much like in a conventional laser. The initial part of this work was published in a conference proceedings article. We found that when the atomic line is extremely narrow, it was possible to have a system in which the coherence is stored in the macroscopic atomic dipole rather than in the optical field. Instead of stimulated emission, which is the key mechanism of lasing, we instead found steady-state superradiance. Furthermore, by adjusting the relative role of the cavity linewidth and atomic linewidth, it was possible to smoothly tune between this exotic superradiant behavior, and the more conventional lasing action.

We have begun to map out and understand the crossover from the conventional laser to the regime of collective superradiant emission. Our approach has been to employ quantum trajectory simulations using the quantum state diffusion approach. In addition we have developed a semiclassical theory capable of dealing with mesoscopic systems. We are currently assembling a paper on this.

Conference presentations

We presented our results in three papers at the DAMOP divisional meeting of the American Physical Society in Atlanta, GA, in June 13–17, 2011, and in an invited talk at the 41st Winter Colloquium on the Physics of Quantum Electronics, PQE-2011, at Snowbird, Utah, January 2–6, 2011.

Postdoctoral and undergraduate students

The STIR support was used to fund the Senior Research Associate, Dominic Meiser, whose research activities were exclusively devoted to this project, and the undergraduate Kayla Crosbie, who completed and defended successfully her Honors Thesis in Physics, graduating with the top award of Summa Cum Laude. She began PhD research at the University of Texas Austin in Fall 2011.

Summary of the most important results

Our analysis of both the active and passive systems has shown that with current experimental technology laser linewidths of about one millihertz can be achieved, whereas linewidths below 1 microhertz are possible in principle.

Since the linewidth of the local oscillator is one of the most fundamental obstacles to improving clocks, as well as the fundamental interest in steady-state superradiance, this topic is important for applications in precision metrology and in the devices and applications that such technology will enable.

References

[1] M. J. Martin, D. Meiser, J. W. Thomsen, Jun Ye, M. J. Holland, "Extreme non-linear response of ultra-narrow optical transitions in cavity QED for laser stabilization", Phys. Rev. A **84**, 063813 (2011).

[2] D. Meiser, J. Ye, and M. Holland, "Prospects for milli-hertz linewidth lasers using collective emission", Proceedings of the 2010 IEEE International Frequency Control Symposium (FCS), Conference Date 1 June, (2010).